MULTI-AXIS VIBRATION MITIGATION PROPERTIES OF SEAT CUSHIONS DURING MILITARY PROPELLER AIRCRAFT OPERATIONAL EXPOSURES

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ABSTRACT

There have been increasing complaints of annoyance, fatigue, and musculoskeletal pain during prolonged exposures to propulsion-generated vibration in military propeller aircraft. The objective of this study was to evaluate the effects of seat cushions on mitigating the higher frequency (>10 Hz) multi-axis vibration associated with Navy E-2C Hawkeye operations. An E-2C crew seat was used in the laboratory during exposure to a selected operational signal. Triaxial accelerations were measured at the interface between the human and cushion (seat pan and seat back). The most pronounced effects were observed at the blade passage frequency (~73.5 Hz). The highest vibration occurred at the seat pan in the fore-and-aft (X) direction of the subject (lateral direction of the aircraft). Substantial vibration was observed at the seat back in the vertical (Z) direction. Significantly lower levels of fore-and-aft (X) vibration occurred at the seat pan with all cushions as compared to the original E-2C cushion ($P<0.05$). The largest reduction in the X acceleration was about 40% with a mean reduction of approximately 20% among the cushions. The results raised questions regarding psychophysical effects and whether the vibration mitigation at the blade passage frequency is sufficient for reducing the reported symptoms.

INTRODUCTION

Back pain in crew members has been documented in both rotary-wing and fixed-wing propeller aircraft[1, 9]. However, poor posture has been identified as the primary contributing factor, particularly in helicopters[1, 6, 8, 9]. More recently, increasing reports of annoyance, fatigue, and even symptoms of back pain have received more serious attention in propeller aircraft. These symptoms have been associated with increased aircraft vibration and exposure to longer missions associated with current international affairs. One particular case involves the U.S. Navy E-2C Hawkeye, a carrier-based early warning command and control platform. The Navy conducted a survey of 185 E-2C aviators that included 42% Pilots/Copilots and 58% Navy Flight Officers or NFOs. The results indicated that 80% of the respondents had experienced neck and/or back pain in a one-year period[5]. The majority of these individuals indicated that the pain lasted for at least

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one to two days. Thirty-five to 40% of those reporting pain considered the symptoms a limiting factor in job performance.

A vibration survey was conducted by this laboratory to measure the seat accelerations in the E-2C[12] . The study confirmed that the vibration associated with the propulsion system in this aircraft consistently occurred at ~18.5 Hz (rotor speed) and ~73.5 Hz (blade passage frequency). Vibration at these frequencies can be felt by the occupant[12]. The measurements indicated that the highest vibration at the NFOs' locations occurred in the lateral (Y) direction of the aircraft. Since the NFOs were rotated 90 degrees during flight, this vibration occurred in the fore-and-aft (X) direction relative to the seated occupant. The lowest vibration occurred along the longitudinal axis of the aircraft.

Seat cushions have been considered a low-cost strategy for improving comfort and mitigating certain vibration. Conventional cushions typically increase the transmission of vertical vibration at low frequencies in the vicinity of the primary human whole-body resonance (4-8 Hz) and attenuate the transmission of vibration at higher frequencies[3, 7, 10, 11]. A study conducted in this laboratory evaluated the transmission of vibration to the seated occupant of several selected military seat pan cushions[13]. The exposures were limited to vertical vibration between 1 and 80 Hz. The results suggested that certain cushions, while amplifying the vibration at low frequencies, could substantially dampen the vibration at higher frequencies associated with propeller aircraft. The objective of this study was to evaluate the effects of selected cushions on reducing higher frequency multi-axis vibration. The ISO 2631-1: 1997[4] was used to assess the subjective comfort and psychophysical effects of the vibration. This paper reports the results for exposure to an operational signal collected on the E-2C Hawkeye.

METHODS AND MATERIALS

Equipment and Instrumentation

Figure 1. Subject Seated in the E-2C Seat

The study was conducted on the Six Degrees-of-Freedom Motion Simulator (SIXMODE) located at the Air Force Research Laboratory, Human Effectiveness Directorate (AFRL/HEPA). An E-2C seating system was acquired for the study. Figure 1 illustrates a subject seated in the E-2C seat mounted onto the SIXMODE. Six seat cushion configurations were tested in the E-2C seat, including the original E-2C seat pan cushion. Table 1 lists the seat cushion configurations. Configurations A – E consisted of seat pan cushions with the original E-2C seat back cushion. Configuration F (E-2C prototype ensemble) consisted of the E-2C prototype seat pan cushion used in Configuration E and an E-2C prototype seat back cushion. Cushion A, the original E-2C seat pan cushion, was a flat cushion fabricated of conventional polyurethane foam. A thin stiff material was located at the leading edge of the top of the cushion. The cushion was approximately 5.5 cm in thickness, weighed 1.74 kg, and was covered with fabric.

Table 1. Cushion Configurations

Cushion Configuration	Description
A	Original E-2C
B	AH-64 Prototype
C	F/A-22 ACESII
D	Supracor® Slimline
E	E-2C Prototype (Seat Pan Only)
F	E-2C Prototype (Ensemble)

The E-2C seat back cushion, used with Configurations A – E, consisted of a thin layer of polyurethane foam approximately 1 cm in thickness, weighed 0.414 kg including the lumbar support, and was covered with fabric. The separate contoured lumbar support was made of conventional foam about 2-4 cm thick, covered with fabric, and attached to the seat back cushion with snaps. Configuration B was an AH-64 (Apache) prototype seat pan cushion fabricated with a top layer of polyurethane foam about 1 cm thick, a middle layer of rate-sensitive foam about 4 cm thick at the center back, and a bottom layer of stiff foam with air vents about 3.5 cm thick at the center back. An air bladder, designed to provide thigh support, was located inside the cushion towards the front edge. The air bladder was deflated during the study. The cushion weighed 1.70 kg including the inflator hose and bulb, and was covered with a thick wool-type material. Configuration C was an operational seat pan cushion selected for use in the F/A-22 ACESII ejection seat. The cushion was constructed of stiff rate-sensitive foam contoured from 2.5-5.0 cm thick, sealed in a 0.5 cm layer of polyurethane foam, and encased in a fabric cover. It weighed 1.18 kg. Cushion D was a commercially-available seat cushion made of two layers of urethane honeycomb air cells. It was approximately 4 cm thick, weighed 1.23 kg, and included a fabric cover. Configurations E and F were prototype cushions developed for specific use in the E-2C aircraft. The contoured seat pan cushion was comprised of a top layer of about 1 cm of polyurethane foam, a middle layer of rate-sensitive foam, and a thin bottom layer of a stiff, rubber-like material. The seat pan cushion ranged from about 5–9 cm in thickness and weighed 1.57 kg. The seat back cushion was made of rate-sensitive foam about 2.5–5 cm in thickness and contoured for lumbar support. The seat back cushion weighed 1.24 kg. Both cushions were covered with fabric. All seat cushions were attached to the seat pan with double-sided adhesive tape to prevent slippage.

Triaxial accelerometer packs were attached to the floor using double-sided adhesive tape. These packs consisted of three orthogonally-arranged miniature accelerometers (Entran EGAX-24, Entran Devices, Inc., Fairfield, NJ) embedded in a Delrin® cylinder measuring 1.9 cm in diameter and 0.86 cm in thickness, and weighed approximately 5 gm. Triaxial accelerometer pads were secured to the top of the selected cushion at the seat pan and seat back using double-sided adhesive tape and duct tape. Each pad consisted of a flat rubber disk approximately 20 cm in diameter and weighing approximately 355 gm. Embedded in the disk was a triaxial accelerometer pack.

Seven subjects (4 females and 3 males) weighing between 53.5 kg and 101.6 kg participated in the study. Subjects were members of the Impact Acceleration Panel at Wright-Patterson AFB, OH. The study was approved by the Institutional Review Board (IRB) at Wright-Patterson AFB. The subjects were instructed to maintain an upright posture in contact with the seat back.

Biodynamic Data Collection and Processing

During this study, subjects were exposed to several types of signals, including two 20-s E-2C operational signals. This paper reports the results of exposure to one of the E-2C signals collected during the Loiter phase of flight onboard the E-2C aircraft[12]. Loiter represented the mission flight scenario for the aircrew and most of the flight time is expected to be spent at this flight condition. The signal was regenerated at 1024 samples-s^{-1} in all three axes on the SIXMODE. The acceleration data were collected for 20 s, low-pass filtered at 100 Hz, and sampled at 1024 samples-s^{-1}. MATLAB® was used to estimate the constant bandwidth power spectral density (psd) using Welch's method[15] at the floor, seat pan and seat back. The time histories in each direction were divided into 2-s segments with 50% overlap. A Hamming window was applied to the segments and the resultant power spectral densities averaged for the 20-s exposure. The root-mean-square (rms) acceleration frequency spectra in the fore-and-aft (X), lateral (Y), and vertical (Z) directions (relative to the seated occupant) were calculated as:

$$a_{rms_i} = \sqrt{(a_{psd_i} * 0.5)} \tag{1}$$

where *i* represents the ith frequency component and 0.5 is the frequency resolution in Hertz (Hz). The 20-s acceleration time histories were also analyzed in one-third octave proportional frequency bands using a software program developed by Couvreur[2]. The program uses MATLAB® routines to generate the rms acceleration level in each one-third octave band (reported at the center frequency) in each direction. The program was modified to include frequencies below 25 Hz. In order to assess the psychophysical effects of the frequency components of interest, and to evaluate human comfort, the rms acceleration spectra in each direction at the seat pan and seat back were weighted as follows:

$$a_{wrms_i} = \lfloor w_{ji}\, a_{rms_i} \rfloor \tag{2}$$

where *i* represents the center frequency component and *j* represents the particular frequency weighting depending on the measurement site (seat pan or seat back) and direction. The weighted values were used to predict subject sensitivity to the major frequency components for each cushion using the appropriate multiplying factors depending on the location and direction (psychophysical effects). These frequency weightings and multiplying factors are given in ISO 2631-1: 1997[4]. The overall weighted rms acceleration level in each direction was calculated between 1 and 80 Hz as:

$$a_w = \left[\sum_i a^2_{wrms_i} \right]^{1/2} \tag{3}$$

The Vibration Total Value (*VTV*) was calculated at the seat pan and seat back as

$$VTV = \sqrt{k^2 a^2_{wx} + k^2 a^2_{wy} + k^2 a^2_{wz}} \tag{4}$$

where *k* is the multiplying factor associated with a particular direction and location. The overall *VTV* was calculated as the vector sum of the seat pan *VTV* and seat back *VTV*[4].

The Repeated Measures Analysis of Variance, Bonferroni Comparison Test, and Paired t-Test were used for the statistical analysis. Significance effects were defined for $P < 0.05$.

RESULTS

Input Frequency Spectra

Figure 2 illustrates the sample input or floor constant bandwidth spectra in the X, Y, and Z directions (relative to the seated occupant) for four of the seven subjects. The figure shows that the input signal characteristics were quite similar among the subjects. For the selected signal, the

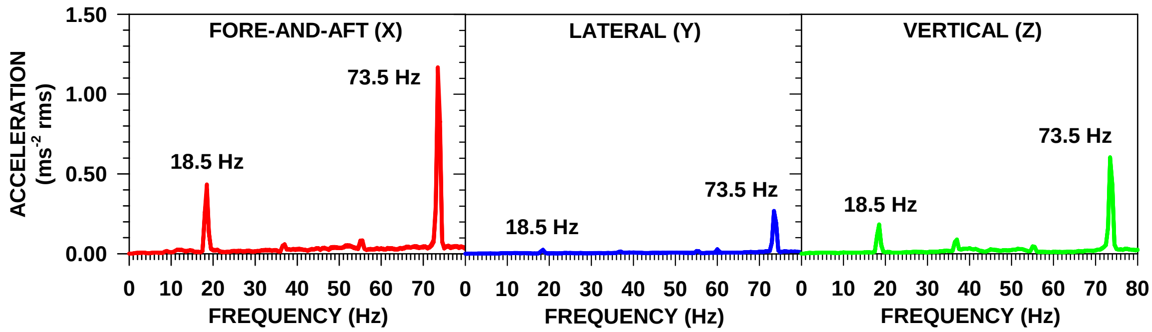


Figure 2. Acceleration Frequency Spectra for theE-2C Hawkeye Input Signal

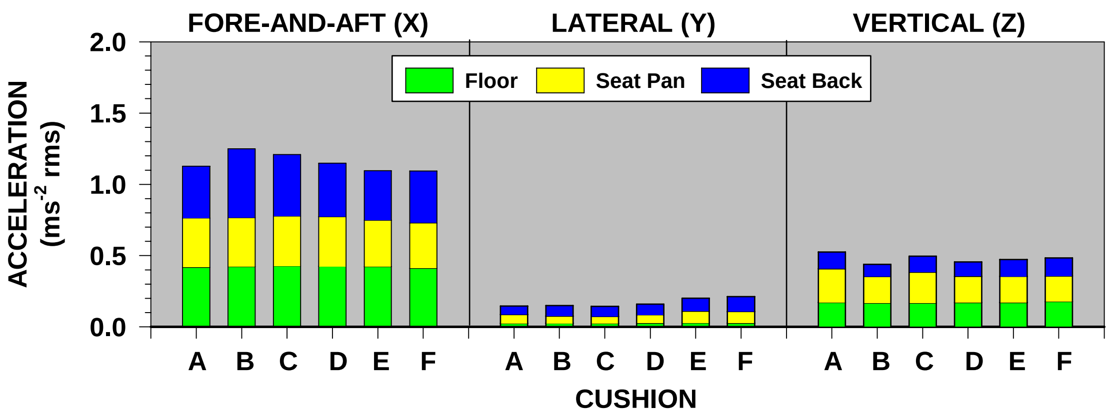
highest vibration levels occurred in the X direction of the occupant or the Y direction of the aircraft. The lowest levels occurred along the longitudinal axis of the aircraft. The figure shows the distinct peak occurring at 18.5 Hz associated with the rotor speed and the distinct peak occurring at 73.5 Hz associated with the blade passage frequency.

Seat Cushion Biodynamic Effects

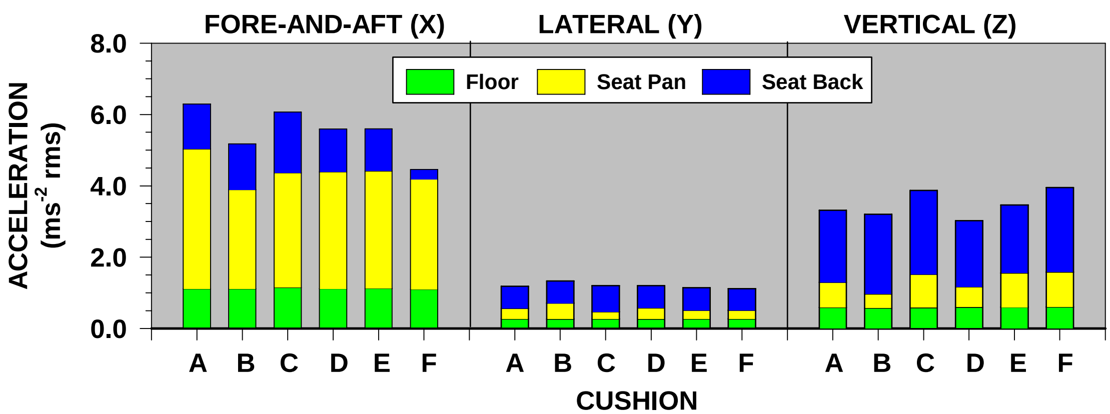
Figure 3 illustrates the mean floor (input), seat pan (pan), and seat back (back) rms acceleration levels in each direction at the rotor speed (Figure 3a) and blade passage frequency (Figure 3b) for each cushion.

The floor data showed the higher aircraft vibration levels occurring in the X direction at both frequency components as observed in Figure 2. There were no significant differences in the floor acceleration levels at either the rotor speed (18.5 Hz) or blade passage frequency (73.5 Hz) in any respective direction, indicating, as shown in Figure 2, that the input signal was similar among the subjects and cushions.

The highest vibration at the rotor speed occurred in the X direction at both the seat pan and seat back (Figure 3a). Although not statistically compared, the seat pan and seat back acceleration levels in the X direction appeared to be similar to or lower than the floor levels with some exceptions (Cushion B seat back) (noted in mean data shown in Figure 3a). At the seat pan, there were no significant differences in the rotor speed accelerations among the cushions in the X direction as well as in the Y direction, with mixed results in the Z direction where all cushions except Cushion C showed significantly lower acceleration levels as compared to Cushion A, the original E-2C cushion. The differences were not dramatic, as shown in Figure 3a. At the seat back, no significant differences were found at the rotor speed in the X or Y acceleration levels among the cushions. One subject did show relatively high seat back accelerations with Cushions



a. Rotor Speed (18.5 Hz)



b. Blade Passage Frequency (73.5 Hz)

Figure 3. Mean Floor, Seat Pan, and Seat Back Accelerations

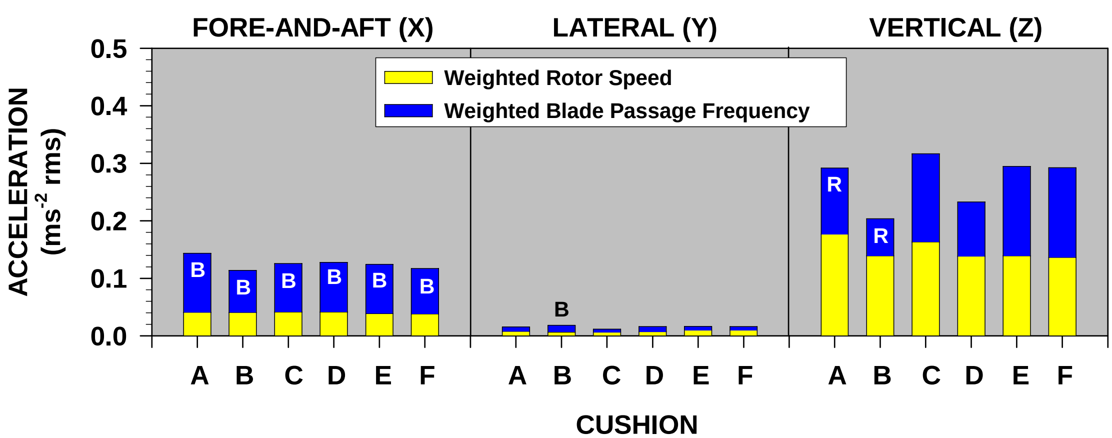
B and C in the X direction. These data were eliminated from the mean values at the seat back in Figure 3a. Cushion B did tend to show the lowest seat back acceleration levels in the Z direction at the rotor speed. These results were significant when compared to three of the tested cushions, including Cushions A, E, and F.

At the blade passage frequency, substantially higher seat pan vibration occurred in the X direction of the seated occupant as compared to the input at the floor regardless of the cushion configuration (Figure 3b). In addition, the X-axis acceleration level at the blade passage frequency was significantly lower for all seat cushion configurations as compared to Cushion A, the original E-2C cushion. The greatest reduction in acceleration was about 40% with a mean reduction of approximately 20% among all of the cushions. Mixed results occurred in the Y and Z direction; several cushions showed similar acceleration levels, including Cushion A. The seat back vibration in the X direction appeared to be lower as compared to the seat pan. The most dramatic effect at the seat back was the significantly lower fore-and-aft (X) acceleration level occurring at the blade passage frequency with the use of Cushion F as compared to the other cushion configurations. Except for Cushion F, the lowest seat back vibration tended to occur in the Y direction; no significant differences were observed among the cushion configurations.

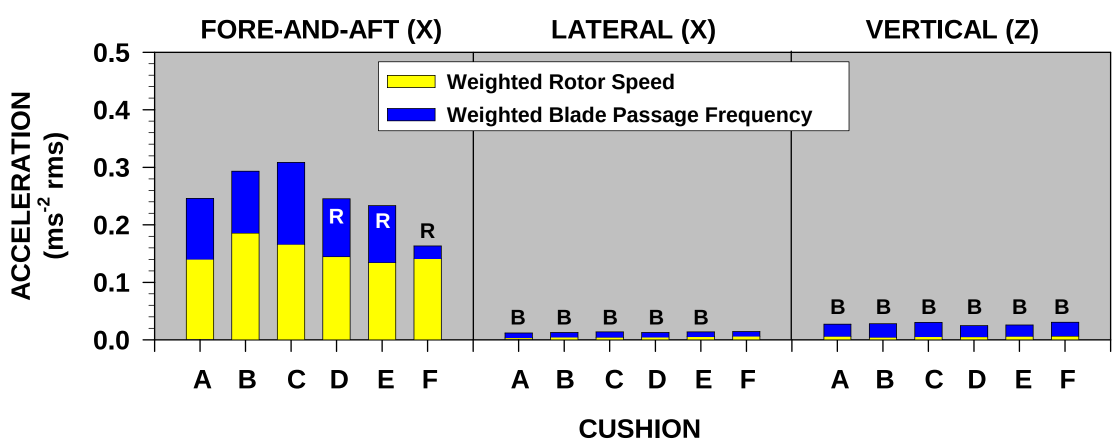
In contrast to the seat pan, Figure 3b shows that, at the seat back, the highest accelerations associated with the blade passage frequency occurred in the Z direction with no significant differences observed among the cushion configurations. The vertical (Z) vibration appeared to be amplified at the seat back as compared to the input at the floor (Figure 3b).

Psychophysical Effects

The frequency weightings and multiplying factors given in ISO 2631-1: 1997[4] suggest that frequency components with similar weighted acceleration levels should be equal with respect to human perception or sensitivity to the vibration. Figure 4 illustrates the mean weighted acceleration levels (based on the center frequency of the respective one-third octave band) at the rotor speed (20 Hz) and blade passage frequency (80 Hz) at the seat pan and seat back for each of the tested cushion configurations. Although not statistically compared, the weighted values in



a. Seat Pan



b. Seat Back

Figure 4. Mean Weighted Acceleration Level at the Rotor Speed and Blade Passage Frequency, a. Seat Pan, b. Seat Back

Figure 4a suggest that the vertical (Z) accelerations would be perceived as being higher as compared to the fore-and-aft (X) accelerations at the seat pan, in contrast to the results shown in

Figure 3. The Paired t-Test indicated that, at the seat pan, the fore-and-aft (X) vibration associated with the blade passage frequency would be perceived as being higher for all tested cushions (as annotated with an ‘B’) as compared to the fore-and-aft (X) vibration associated with the rotor speed. Most cushions showed no difference in the perceived vibration of the two frequency components in the vertical (Z) direction. The original E-2C cushion did show that, at the seat pan, the vertical (Z) vibration associated with the lower frequency rotor speed would be perceived as being higher (as annotated with an ‘R’) than the vertical (Z) vibration at the blade passage frequency. In contrast to the results at the seat pan, Figure 4b strongly suggests that the fore-and-aft (X) vibration at the seat back would be perceived as being much higher than the vibration in the other directions. Fifty percent of the cushions showed that the levels of the two frequency components in the fore-and-aft (X) direction would be perceived similarly, while the remaining showed that the vibration associated with the rotor speed would be perceived as being higher (as annotated with an ‘R’). This was of particular interest with Cushion F, which included a prototype seat back cushion. Although the weighted seat back vibration in the Y and Z directions was quite low, the results showed that the perception of the blade passage frequency (B) was significant in most cases.

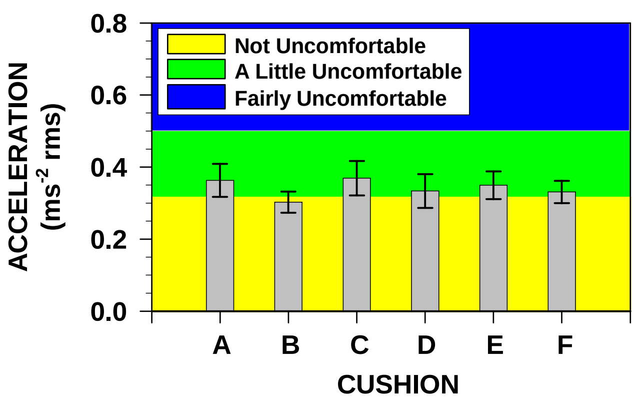


Figure 5. Mean Overall VTV +/- One Standard Deviation

Figure 5 illustrates the overall Vibration Total Values (VTV) +/- one standard deviation for each cushion configuration. The figure shows that, for most subjects, all tested cushions or configurations would be considered “a little uncomfortable” in accordance with the guidelines given in ISO 2631-1: 1997[4]. The statistical analysis showed that Cushion A and Cushion C showed significantly higher VTVs as compared to Cushion B (excluding the calculation using the seat back data from one subject for Cushions B and C as described above). The VTVs for all other configurations were similar. While not shown, the VTV calculated for the seat pan alone showed that the majority of subjects would consider the vibration “not uncomfortable” for all configurations. Similar statistical findings were observed for the VTVs calculated using the seat pan data only as compared to the overall VTVs which included the seat pan and seat back data.

DISCUSSION

This study investigated the effects of selected seat cushions on reducing higher frequency multi-axis vibration associated with the propulsion system in military propeller aircraft. The psychophysical effects of the vibration were also evaluated. For the selected exposure, this study showed that the most notable effects of seat cushions on the transmission of vibration to the occupant occurred at the higher frequency component or the blade passage frequency. In addition, the highest vibration at this frequency (73.5 Hz for the E-2C exposure) occurred at the seat pan in the fore-and-aft (X) direction. This has also been shown to be the case at the side

passenger seats located in the propeller plane of C-130 variants[14]. At the blade passage frequency, all cushions were capable of reducing the fore-and-aft (X) vibration as compared to the original E-2C cushion for the particular exposure used in this study. Although not reported in this paper, the unweighted overall acceleration levels (calculated in accordance with Equations 3 and 4 but excluding the frequency weightings and multiplying factors) also showed the significant reduction with all seat pan cushions as compared to the original E-2C cushion (Cushion A). The issue of vibration mitigation via the seat pan cushion becomes more complex when considering the transmission of vibration at the seat back. For the exposure used in this study, relatively high vertical vibration was transmitted to the occupant via the seat back at the blade passage frequency. Although not affecting the vertical vibration at the seat back, Cushion F, which included the prototype seat pan cushion (Cushion E) and a prototype seat back cushion, did show substantial damping of the fore-and-aft (X) seat back vibration.

The summary of results given above suggests that any of the tested cushions would reduce at least some vibration as compared to the original E-2C seat cushion, particularly the higher fore-and-aft (X) accelerations that are transmitted at the blade passage frequency. However, the human body is sensitive to the frequency, direction, and location of the vibration as described in the ISO 2631-1: 1997[4]. The weightings of the vibration levels measured during Loiter at the three NFO seat pan locations during actual flight indicated that the crew members would perceive the rotor speed vibration as being more pronounced in both the fore-and-aft (X) and vertical (Z) directions (using an E-2C cushion). In this study, this was true only in the vertical (Z) direction. These results may have been influenced by the selection of the particular signal for use in the study. The relative contributions of vibration associated with the rotor speed and blade passage frequency are expected to vary depending on flight conditions. Regardless, the results of this study, as well as a previous study using only vertical (Z) vibration[13], suggest that current seat cushion designs may be more effective at reducing vibration associated with higher frequency components in the vicinity of the blade passage frequency.

The inclusion of the weighted seat back accelerations in the calculation of the overall Vibration Total Value (VTV) did influence the perception of comfort based on the ISO 2631-1: 1997[4] by at least indicating that the vibration would be considered "a little uncomfortable." Both the seat pan VTV and overall VTV showed a reduction in vibration only with Cushion B as compared to Cushion A relative to human perception. The Navy report suggested that the vibration may be contributing to symptoms of low back pain[5], suggesting that the vibration would be perceived as being more than just a little uncomfortable during military operations. The question is raised as to whether the weighting curves and multiplying factors given in the standard[4] effectively reflect the perception of vibration at higher frequencies, particularly during the operation of military propeller aircraft over prolonged periods of time.

The psychophysical effects related to vibration frequency, direction, and location render it difficult to determine an appropriate strategy for mitigating higher frequency vibration associated with propeller aircraft, even though cushion design may be able to substantially reduce the vibration of specific frequency components. Newer seat designs, including active or semi-active vibration isolation of the seating system, could potentially mitigate the higher frequency vibration associated with the propulsion system and improve comfort. However, these systems must consider crashworthiness. Other strategies include periodic balancing of the propellers,

which has been shown to reduce the rotor speed vibration in certain aircraft[14]. Regardless of the mitigation strategy, a reduction in human vibration exposure during prolonged missions would likely contribute to improving crew comfort and health.

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the funding agency.

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